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Mangrove gastropod distribution based on dominant vegetation classes and their relationship with physicochemical characteristics on fringe mangroves of Lembongan Island, Bali, Indonesia

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Abstract. *Ernawati NM, Dewi APWK, Sugiana IP, Dharmawan IWE, Ma'ruf MS, Galgani GA. 2024. Mangrove gastropod distribution based on dominant vegetation classes and their relationship with physicochemical characteristics on fringe mangroves of Lembongan Island, Bali, Indonesia. Biodiversitas 25: 142-152.* Mangrove ecosystems are important in supporting diverse marine life, offering refuge, reproductive grounds, and sustenance to various species. However, mangroves possess distinct zoning patterns determined by dominant species due to environmental variations that significantly impact the biodiversity of biota, particularly gastropods. A study on the Indonesian island of Nusa Lembongan revealed distinct communities of coexisting gastropod species in each mangrove vegetation zone. We discovered 29 distinct species of mangrove gastropods, with the *Sonneratia* mangrove zone having the most and the *Lumnitzera* zone having the least. Certain species, including *Amphidromus perversus*, *Cerithium adustum*, and *Echinolittorina sundaica*, were detected in only one of the mangrove zones. In each mangrove zone, the composition of gastropod species changed depending on the substrate type, e.g., soil, mangrove trunks, or mangrove leaves. The Shannon-Wiener diversity index values range from low to high diversity, and the community structure index values in mangrove zones vary. The evenness index varied by region, with *Avicennia*, *Bruguiera*, and *Sonneratia* having the highest index value. The findings indicate that mangrove vegetation zones are essential for maintaining diverse gastropod populations, with distinct composition and abundance patterns influenced by the distance of each mangrove zone from the ocean. This data may influence conservation efforts to preserve mangrove habitats and the diverse array of organisms that depend on them.

Keywords: Abundance, composition, mangrove zones, Shannon-Wiener diversity index

INTRODUCTION

Mangrove habitats are crucial in supporting various marine creatures, serving as vital ecosystems for numerous species. These coastal ecosystems are teeming with life, providing refuge, reproductive grounds, and sustenance for a diverse range of organisms, as highlighted by researchers (Nagelkerken et al. 2008; Kathiresan 2012; Hutchison et al. 2014; Rajpar and Zakaria 2014). Fish, crabs, shrimp, mollusks, and a myriad of other marine organisms rely on mangroves for their survival and growth. One of the remarkable features of mangroves is their intricate root systems, which serve as a haven for young fish and tiny benthic organisms, offering protection from predators and a source of food (Nagelkerken et al. 2008; Kon et al. 2009; Whitfield 2017). Additionally, mangroves contribute to water quality by filtering sediments and nutrients, which helps reduce the number of contaminants that harm marine life (Buhmann and Papenbrock 2013; Cochard 2017). The health of marine ecosystems is intrinsically linked to the presence and well-being of mangrove forests, as they provide critical support for many species (Rog et al. 2017).

The survival and well-being of gastropods are inextricably linked to the health and persistence of mangrove ecosystems. A growing body of research, as indicated by Kabir et al. (2014) and Hasidu et al. (2020), underscores that the diversity of gastropods thrives in undisturbed mangrove forests, highlighting the detrimental impact of degradation and conversion to alternative land uses. Mangroves offer a haven for gastropods, creating secure environments for feeding and reproduction. These coastal forests provide gastropods with essential sustenance, as the decomposition of leaves and organic matter in mangrove environments generates a nutrient-rich food source for these organisms, a fact emphasized in studies such as Ong and Gong (2013) and Rajpar and Zakaria (2014). Moreover, the extensive and intricate root systems of mangroves play a pivotal role in shielding gastropods from predators and harsh marine conditions, a safeguarding effect examined by Whitfield (2017).

The distribution of gastropods within mangrove ecosystems exhibits a complex interplay of factors, making it a subject of intricate study and paramount importance in habitat conservation. This distribution pattern is not uniform and varies according to the specific type of mangrove ecosystem under consideration. Kabir et al. (2014) and Nurfitriani et al. (2019) have observed substantial discrepancies in the quantity and diversity of gastropods among different prominent mangrove species, highlighting the intricacies of these ecosystems. A multitude of variables come into play, impacting the distribution of gastropods. Both physical elements, such as temperature, salinity, and water depth, and biological factors, including predation and competition (Imamsyah et al. 2020), contribute to these patterns. Furthermore, Kabir et al. (2014) documented that anthropogenic influences such as pollution and habitat destruction add complexity to gastropod distribution in mangrove environments.

Nusa Lembongan, an island off the southern coast of Bali, stands as a remarkable hub of biodiversity, hosting a wealth of newly discovered mangrove species. This peripheral mangrove ecosystem is predominantly characterized by the presence of *Avicennia*, *Bruguiera*, *Ceriops*, *Lumnitzera*, *Rhizophora*, *Sonneratia*, and *Xylocarpus*, as detailed in Palguna et al. (2017) and included as protected forest supervised by Klungkung District Government, Bali Province. The unique feature of Nusa Lembongan's mangroves lies in the distinctive zonation pattern displayed by each of these mangrove taxa, a pattern intricately linked to the island's proximity to the surrounding waters. This zoning structure plays a pivotal role in preserving the integrity of the island's mangrove ecosystems. Furthermore, the thriving mangroves on Nusa Lembongan extend their benefits beyond the ecological sphere. They play a significant role in boosting the local economy providing resources and opportunities that positively impact the livelihoods of the island's residents. The multifaceted role of Nusa Lembongan's mangroves underscores the island's ecological and socio-economic significance, making it a pivotal area for ongoing regional study and conservation efforts.

This study seeks to determine how the subdivision pattern of mangrove species influences the species abundance and distribution of gastropods. On Nusa Lembongan, six mangrove zones were selected to represent the overall condition of the mangrove ecosystems. Understanding the effect of mangrove zoning on the distribution of marine gastropods is essential for effectively managing and conserving these essential ecosystems. Such knowledge could aid in developing management strategies that account for the local distribution of marine gastropod populations in diverse mangrove forest zones.

MATERIALS AND METHODS

Study area

Six mangrove zones on Nusa Lembongan (8.663148°S-8.694237°S, 115.446668°E-115.473524°E) were selected based on the dominant vegetation genus *Avicennia, Bruguiera, Ceriops, Lumnitzera, Rhizophora, Sonneratia* mangrove zones. Each zone was divided into five 10 x 10 m plots with a minimum distance of 20 meters between each plot (Figure 1). We also used Google Earth Pro to compute the distance between each plot and the sea based on its perpendicular location (Table 1). The sampling was conducted from January to March of 2022.

Gastropods data sampling and analysis

Under low tide conditions, gastropods on the substrate (soil, mangrove trunks, and leaves) were collected by scouring the soil to a depth of 5cm with a metal scraper and handpicking gastropods from mangrove trunks and leaves. The boundary of the gastropod sampling area was delineated by a 1 x 1 meter transect repeated three times within each 10 x 10-meter plot of mangrove vegetation. Since gastropods were not found on all repetitions of each subplot, the gastropod discovery data was combined into one between subplots, with a total sample of 30 plots (5 in each zone). The collected gastropods were deposited in plastic containers marked with the plot number and sampling date and then identified using Robin's book "Compendium of Marine Gastropods" (2021). Using the Shannon-Wiener Index, the obtained data were analyzed to ascertain the gastropod community structure (diversity, uniformity, and dominance), and the abundance value was obtained by dividing the number of gastropod species per area (m^2) of each mangrove zone.

Forest structure measurement

Moreover, 5 of 10 x 10-meter quadratic plots were established in each zone dominated by a particular genus. Several metrics, including tree class density (Diameter Breast High (DBH)>5 cm), sapling density (DBH<5 cm), seedling density (height 1 m), stem diameter, height, percentage of canopy cover, and mangrove vitality, were determined (Dharmawan and Ulumuddin 2021). Species identification was conducted for each measured stand according to Tomlinson (2016) and Kitamura et al. (1997). The DBH of each stand was measured and categorized as a tree and sapling on each tract. Furthermore, using a trigonometric technique, the height of the mangrove community in each zone was estimated by measuring numerous angles of the forest canopy from a distance of 10 meters. The canopy coverage of mangroves in each zone was estimated using hemispheric imagery. The field data measurement was recorded and processed using the MonMang 2.0 app.

Table 1. The mean and standard deviation of all sample plots' distances from the sea

Zone	Distance from the sea (km)
Avicennia	1.76±0.10
Bruguiera	0.44±0.18
Ceriops	0.88±0.33
Lumnitzera	1.19±0.50
Rhizophora	0.50±0.69
Sonneratia	0.02±0.02

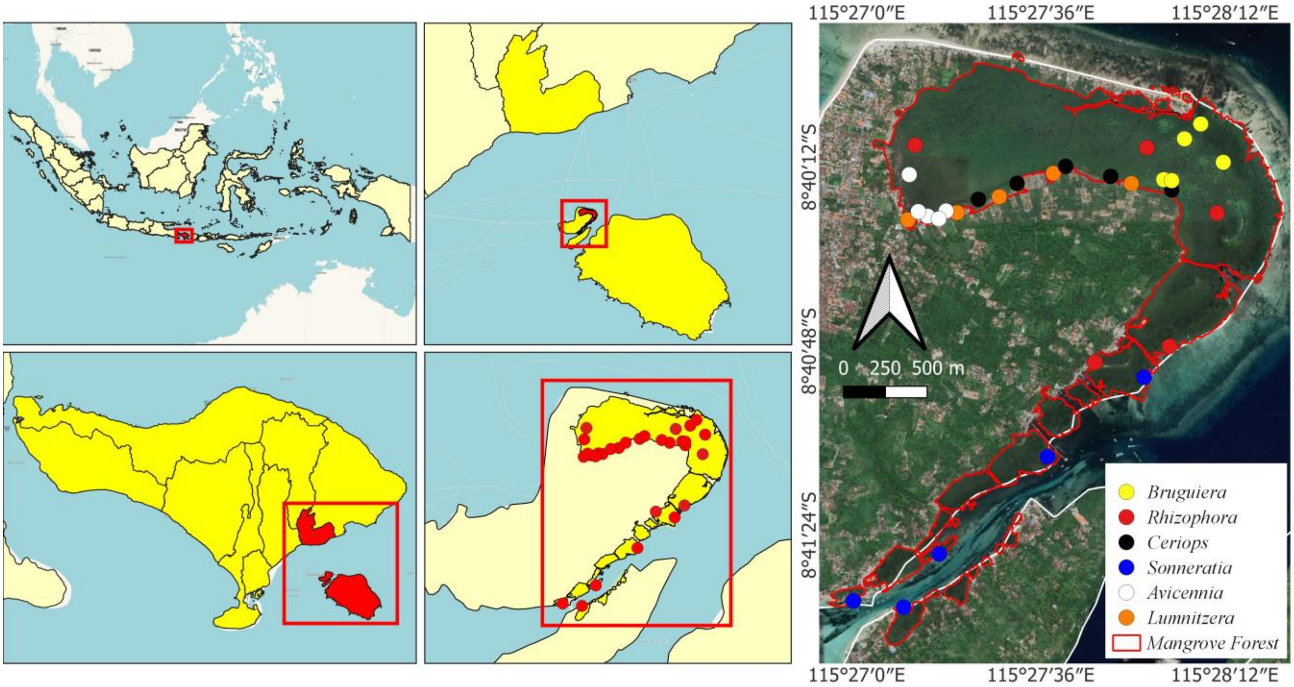

Figure 1. Distribution of sampling plots of each mangrove zone in Lembongan Island, Bali, Indonesia

Soil and pore water physicochemical characteristics

Soil and pore water were analyzed for environmental parameters using a soil drill with a 5 cm diameter and a 100 cm depth; soil samples were obtained for pH testing with a Lutron pH meter 212. Next, 100 grams of soil were desiccated at 70°C for 48 hours to constant weight for Total Organic Matter (TOM) and Total Kjeldahl Nitrogen (TN) analyses. TOM was analyzed by titration, which resulted in Total Organic Carbon (TOC) when multiplied by 0.49 (Chen et al. 2014), whereas TN was determined by the FIA (Flow injection analysis) method. The pore water was promptly measured for temperature, pH, salinity, and Oxidation-Reduction Potential (ORP) using a calibrated Multimeter COM-600 Water Quality Tester at 0-100 cm depth after collecting the soil samples.

Statistical analysis

The Shapiro-Wilk test for normality was applied to all univariate data for Analysis. We used Analysis of Variance (ANOVA) and the Tukey-HSD test to ascertain the significance level because all of the data were normally distributed ($\rho<0.05$). The Pearson correlation test was used to establish the relationship between the abundance of gastropods and ecological factors. All analyses were conducted utilizing R Software version 4.0.2 (Lubis 2021) and a statistical significance level 0.05.

RESULTS AND DISCUSSION

List of discovered gastropods

Nusa Lembongan was a habitat for 29 distinct mollusk species, which varied according to mangrove vegetation types. The *Sonneratia* mangrove zone contains the most gastropod species, with 21 species, while *Lumnitzera* has the fewest, with only three species. There are 13 gastropods species found only in one of the mangrove zones: *Amphidromus perversus*, *Cerithium adustum*, *Echinolittorina sundaica*, *Mitrella ocellata*, *Nerita albicilla*, *Nerita chamaeleon*, *Nerita undata*, and *Pseudovertagus aluco*, which were only found in the *Sonneratia* zone, *Euplica scripta*, *Nerita planospira*, and *Nerita savieana* in the *Rhizophora* zone, and two species: *Cerithium coralium* and *Terebralia palustris* which were only found in the *Avicennia* zone (Table 2).

This study has found 29 gastropods that live in Nusa Lembongan, and various gastropods are abundant in mangrove habitats. In comparison, Octavina et al. (2019) detected only 4 gastropod species in the mangrove forest of Pulo Sarok Aceh, while Bahari et al. (2020) and Hilmi et al. (2022) detected 13 and 6 species, respectively, in the mangrove forests of North Coast Jakarta and Mangrove Dumai City, Riau. Moreover, Pratiwi and Ernawati (2016) found six families of mollusks, and Galgani et al. (2023) found 20 gastropod species in the mangrove ecosystem Nusa Lembongan. Meanwhile, in other global mangrove habitats, 65 species of gastropods were discovered in the mangroves of Vietnam's Khanh Hoa Province (Zvonareva and Kantor 2016). Variations in environmental characteristics, such as salinity, temperature, and substrate features, may account for the differences in gastropod diversity among these locations. It should be noted that the number of gastropod species detected at a specific site can also differ based on the sampling techniques employed. Changes in sampling effort, time of year, and placement of samples within the mangrove ecosystem could all contribute to these differences.

Table 2. Gastropods species checklist of each mangrove zone in Lembongan Island, Bali, Indonesia. (Av: *Avicennia*, Br: *Bruguiera*, Ce: *Ceriops*, Lum: *Lumnitzera*, Rhi: *Rhizophora*, Son: *Sonneratia*)

Species	Av	Br	Ce	Lum	Rhi	Son
Amphidromus perversus (Linnaeus, 1758)	-	-	-	-	-	+
Cassidula nucleus (Gmelin, 1791)	+	+	+	+	+	-
Cerithidea obtusa (Lamarck, 1822)	+	-	-	-	-	+
Cerithium adustum (Kiener, 1841)	-	-	-	-	-	+
Cerithium atratum (Born, 1778)	+	+	+	-	+	+
Cerithium coralium (Kiener, 1841)	+	-	-	-	-	-
Clypeomorus pellucida (Hombron & Jacquinot, 1848)	+	+	+	-	+	+
Euplica scripta (Lamarck, 1822)	-	-	-	-	+	-
Littoraria angulifera (Lamarck, 1822)	-	+	-	-	+	+
Littoraria intermedia (R.A.Philippi, 1846)	-	-	-	-	+	+
Littoraria melanostoma (Gray, 1839)	-	-	-	-	+	+
Littoraria pallescens (R.A.Philippi, 1846)	-	-	-	-	+	+
Littoraria scabra (Linnaeus, 1758)	-	-	-	-	+	+
Echinolittorina sundaica (van Regteren Altena, 1945)	-	-	-	-	-	+
Littoraria vespacea (D.Reid, 1986)	-	-	-	-	+	+
Melampus bidentatus (Say, 1822)	+	+	+	+	-	-
Melampus castaneus (Megerle von Mühlfeld, 1816)	+	+	-	+	-	+
Mitrella ocellata (Gmelin, 1791)	-	-	-	-	-	+
Nerita albicilla (Linnaeus, 1758)	-	-	-	-	-	+
Nerita chamaeleon (Linnaeus, 1758)	-	-	-	-	-	+
Nerita magdalenae (Gmelin, 1791)	-	+	+	-	+	+
Nerita planospira (Anton, 1838)	-	-	-	-	+	-
Nerita savieana (Reeve, 1855)	-	-	-	-	+	-
Nerita undata (Linnaeus, 1758)	-	-	-	-	-	+
Pseudovertagus aluco (Linnaeus, 1758)	-	-	-	-	-	+
Strigatella zebra (Lamarck, 1811)	+	+	+	-	-	+
Telescopium telescopium (Linnaeus, 1758)	+	+	-	-	-	-
Terebralia palustris (Linnaeus, 1767)	+	-	-	-	-	-
Terebralia sulcata (Born, 1778)	+	+	+	+	+	+
Total	11	10	7	4	14	21

Gastropod composition and abundance

The composition of gastropod species varied according to the mangrove zone, which included soil type, mangrove trunks, and leaves. *Terebralia sulcata* dominated the soil substrate of the mangrove zones, including *Avicennia*, *Rhizophora*, and *Sonneratia*, while *Nerita magdalenae*, *Melampus castaneus*, and *Melampus bidentatus* dominated the *Bruguiera*, *Ceriops*, and *Lumnitzera* zones. Around 37% of *T. sulcata* from the total of gastropods found dominated the soil substrate, followed by *Clypeomorus pellucida* (21%) and *Cerithium atratum* (13%). It's similar to Wells (1980), where *T. sulcata* dominated in the *Avicennia* and *Rhizophora* zones, which means this gastropod plays a crucial role in the food cycle in the mangrove soil. In contrast to the soil medium, the vegetation trunks appear to be dominated by different species of gastropods, such as *T. sulcata* in the *Avicennia* and *Lumnitzera* zones, *Cassidula nucleus* and *M. bidentatus* in *Bruguiera* and *Ceriops* zones, *Littoraria vespacea* in *Rhizophora*, and *Clypeomorus pellucida* in *Sonneratia*. *C. pellucida* (35%), *T. sulcata* (14%), and *Littoraria angulifera* (14%) are the three gastropod species that dominate the mangrove trunks. Furthermore, in the *Avicennia* zone, *C. nucleus* was predominated, *M. bidentatus* in the *Bruguiera* and *Lumnitzera* zones, *M. castaneus* in the *Ceriops* zone, and *Littoraria melanostoma* and *Littoraria scabra* in the *Rhizophora* and *Sonneratia* zones, respectively. Overall, three gastropod species from the genus *Littoraria*, namely *L. scabra*, *L. melanostoma*, and *L. angulifera*, predominate in mangrove vegetation leaves, with percentage values of 29%, 26%, and 25%, consecutively (Figure 2). This gastropod genera also plays an important role in consuming living and decaying plants (Reis et al. 2021).

Moreover, the abundance of gastropods differed amongst the major mangrove vegetation types. Gastropods on the mangrove soil significantly differed (ANOVA: $F_{5,5} = 7.187$, $\rho = 3.1 \times 10^{-4}$), especially for the *Sonneratia* zone compared to the other five mangrove zones. Significant variations in trunk and leaf areas were also identified in each mangrove zone (trunk; ANOVA: $F_{5,5} = 11.651$, $\rho = 8.6 \times 10^{-7}$, leaves; ANOVA: $F_{5,5} = 8.788$, $\rho = 7.6 \times 10^{-5}$). *Sonneratia* was the mangrove zone with the highest gastropod abundance in all media, whereas the *Lumnitzera* zone had the lowest (Table 4). The distribution of gastropod abundance is also impacted by the position of each mangrove zonation concerning its distance from the sea (Figure 3).

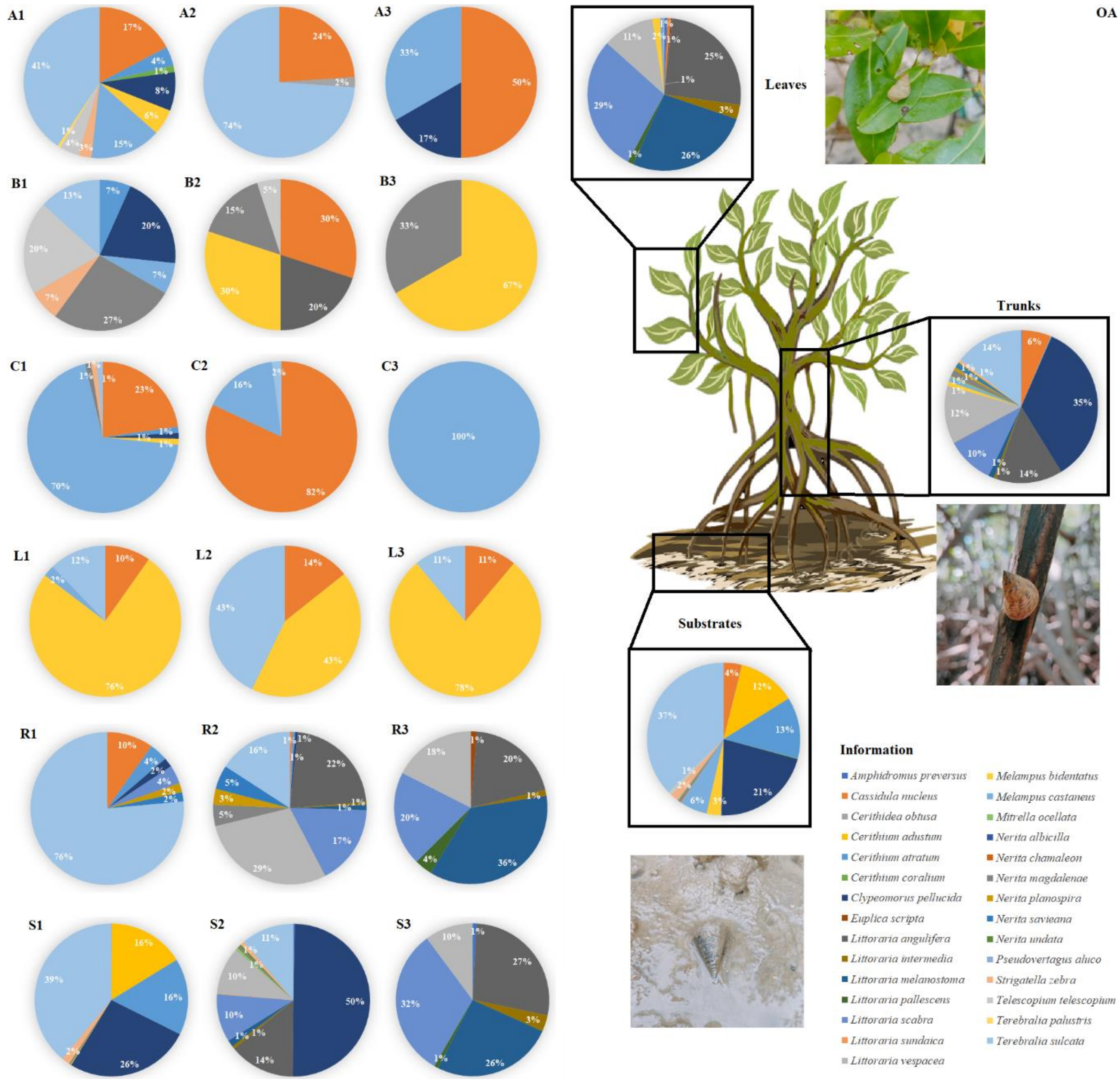

Figure 2. Gastropod species composition in all media (1: Soil, 2: Trunks, and 3: Leaves) and mangrove zones (A: *Avicennia*, B: *Bruguiera*, C: *Ceriops*, L: *Lumnitzera*, R: *Rhizophora*, S: *Sonneratia*, and OA: Overall)

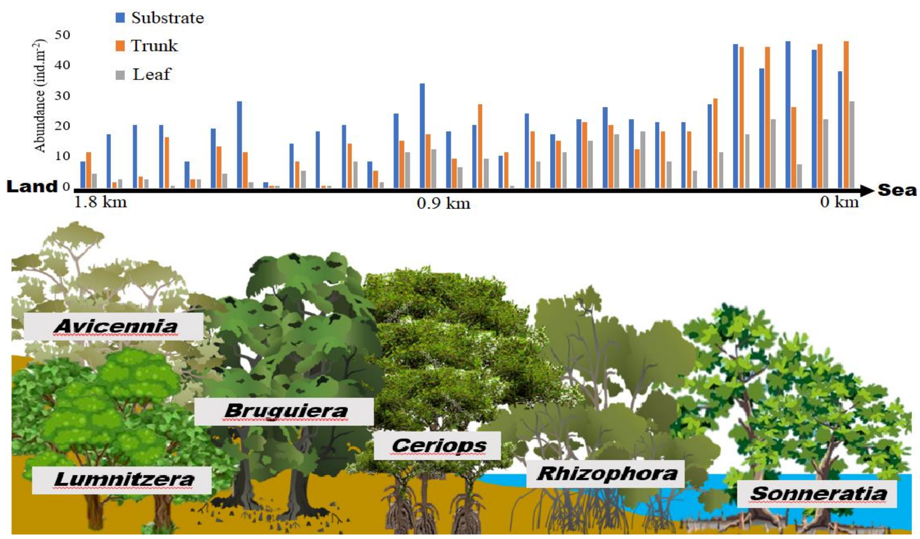

Figure 3. Marine gastropod density is based on dominant mangrove species and distance from the sea in Lembongan Island, Bali, Indonesia. The different colors on the graph indicate the position (soil, stems, and leaves) where the gastropods were found

Table 3. Overall mangrove gastropod composition in all media

Species	**Overall**		
	Soil	**Trunk**	**Leaf**
Amphidromus perversus	0%	0%	1%
Cassidula nucleus	4%	6%	1%
Cerithidea obtusa	0%	0%	0%
Cerithium adustum	12%	0%	0%
Cerithium atratum	13%	0%	0%
Cerithium coralium	0%	0%	0%
Clypeomorus pellucida	21%	35%	0%
Euplica scripta	0%	0%	0%
Littoraria angulifera	0%	14%	25%
Littoraria intermedia	0%	1%	3%
Littoraria melanostoma	0%	1%	26%
Littoraria pallescens	0%	0%	1%
Littoraria scabra	0%	10%	29%
Echinolittorina sundaica	0%	0%	0%
Littoraria vespacea	0%	12%	11%
Melampus bidentatus	3%	1%	2%
Melampus castaneus	6%	1%	1%
Mitrella ocellata	0%	0%	0%
Nerita albicilla	0%	0%	0%
Nerita chamaeleon	0%	0%	0%
Nerita magdalenae	0%	1%	0%
Nerita planospira	0%	1%	0%
Nerita savieana	0%	1%	0%
Nerita undata	0%	0%	0%
Pseudovertagus aluco	0%	0%	0%
Strigatella zebra	2%	1%	0%
Telescopium telescopium	1%	0%	0%
Terebralia palustris	0%	0%	0%
Terebralia sulcata	37%	14%	0%

The distribution of gastropods on these microhabitats indicated that the number of gastropods increases as the surface area increases (Chapperon and Seuront 2011; Tokan et al. 2018). Vegetation types and mangrove locations influence the abundance of gastropods in mangrove ecosystems. For instance, Zvonareva et al. (2015) discovered that the number and species diversity of gastropods in Vietnamese mangrove forests varied between planted mangrove dominated by *Rhizophora apiculata* and associated mangroves (*Rhizophora stylosa* mixed with *Avicennia* sp., *Lumnitzera racemosa*, *Excoecaria agallocha*, *Aegiceras* sp., and *Bruguiera gymnorhiza*). Consistent with the findings of the Nusa Lembongan study (Table 3), the *Sonneratia* zone has the greatest number of gastropods compared to other zones. *Avicennia* had the lowest gastropod abundance in Muara Gembong, West Java (Dwijaya et al. 2021), whereas *Lumnitzera* had the lowest abundance in Nusa Lembongan. The disparities in outcomes may be attributable to geographical and environmental differences between the two research regions as well as the sampling factors previously discussed. In addition, researchers in various regions of Indonesia have uncovered diverse gastropod abundance and species diversity in mangrove habitats. Imamsyah et al. (2020), for instance, identified eleven species of gastropods in the mangrove habitat of Ngurah Rai Grand Forest Park, Bali, with the *Sonneratia* zone comprising the greatest species diversity. Contrary to what was observed on Nusa Lembongan, the *Rhizophora* zone had the least number of gastropods.

In addition, we identified one external factor that contributed to the abundance of gastropods in the Nusa Lembongan mangroves: the presence of birds of prey. According to their imprints, the number of avian predators in the mangrove zone close to human settlements influences the distribution pattern of gastropods, which tends to decrease landward (Figure 4). This may be because gastropods avoid areas with abundant predators. This assumption may be supported by human settlements providing sustenance for avian predators, increasing their population density in the adjacent mangrove zone (Kabir et al. 2014). Therefore, the abundance of these predators may impact the behavior and distribution of gastropods in the mangrove ecosystem. Additional research is required to verify this assumption and determine the extent to which avian predators influence the distribution of gastropods in the mangrove ecosystem.

Gastropods community structure

The community structure indexes showed varied values between mangrove zonation. The Shannon-Wiener diversity index computation produced different values for each zone, ranging from low diversity (H'<1) to moderate diversity (1<H'<3), ranging from 0.40±0.22 to 1.59±0.28. It signifies a small or unstable biota community and a small or unstable distribution of several individuals in each species. Zones with moderate diversity index values included *Avicennia* (1.17±0.06), *Bruguiera* (1.29±0.72), and *Sonneratia* (1.59±0.28), whereas zones with low diversity index values included *Ceriops* (0.40±0.22), *Rhizophora* (0.48±0.13), and *Lumnitzera* (0.53±0.47). Meanwhile, the evenness index in each zone showed a range of values ranging from 0.43±0.11 to 0.74±0.11. The zones with the highest evenness index were *Avicennia* (0.74±0.11), *Sonneratia* (0.70±0.07), and *Bruguiera* (0.69±0.24). *Ceriops* (0.43±0.11), *Lumnitzera* (0.60±0.53), and *Rhizophora* (0.63±0.28) are zones that have an evenness rating in the middle range. The dominance index yields different findings in each zone. *Sonneratia* (0.26±0.08), *Avicennia* (0.37±0.04), and *Bruguiera* (0.39±0.33) have no dominance or no gastropods dominating, but *Lumnitzera* (0.65±0.30), *Ceriops* (0.69±0.26), and *Rhizophora* (0.70±0.13) have the most dominance or gastropods dominating.

The community structure of gastropods in the Nusa Lembongan mangrove vegetation zones is crucial for understanding the distribution of these gastropods at various locations. This mangrove ecosystem is similar to other parts of Indonesia and the rest of the world but also distinct from them. According to Imamsyah et al. (2020), the *Sonneratia* zone in the Ngurah Rai Grand Forest Park, Bali, has the greatest variety of gastropods, followed by the *Rhizophora* zones. Other research conducted in Muara Gembong, West Java mangrove sections revealed that the *Rhizophora* zone has the greatest diversity of gastropods, followed by the *Avicennia* zone (Dwijaya et al. 2021). This lends credence to the conclusion that the gastropod community structure in Nusa Lembongan's mangrove zones exhibited a wide range of diversity, evenness, and dominance indices.

Table 4. Marine gastropods distribution for each zone in Lembongan Island, Bali, Indonesia (superscript letters depict significant differences among zones ρ<0.05)

Objects	Vegetation classes					
	Avicennia	***Bruguiera***	***Ceriops***	***Lumnitzera***	***Rhizophora***	***Sonneratia***
Substrate (ind.m^{-2})	17 ± 8[a]	22 ± 3[a]	23 ± 8[a]	12 ± 8[a]	28 ± 11[ab]	40 ± 8[b]
Stem (ind.m^{-2})	9 ± 6[ab]	21 ± 5[ab]	14 ± 4[ab]	5 ± 5[a]	23 ± 4[b]	40 ± 11[c]
Leaf (ind.m^{-2})	3 ± 1[a]	11 ± 3[ab]	9 ± 3[ab]	2 ± 1[a]	13 ± 7[b]	19 ± 9[b]

Figure 4. Avian footprints discovered in the mangrove zone near the land mangrove zone (*left*), and a long-distance photo of avian discovered in the *Avicennia* zone (*middle, right*)

Table 5. Average value and index criteria of Gastropod Diversity, Uniformity, and Dominance in the Nusa Lembongan Mangrove Ecosystem, Bali, Indonesia

Zone	Diversity (H')	Uniformity (E)	Dominance (C)
Avicennia	1.17±0.06	0.74±0.11	0.37±0.04
Bruguiera	1.29±0.72	0.69±0.24	0.39±0.33
Ceriops	0.40±0.22	0.43±0.11	0.69±0.26
Lumnitzera	0.53±0.47	0.60±0.53	0.65±0.30
Rhizophora	0.48±0.13	0.63±0.28	0.70±0.13
Sonneratia	1.59±0.28	0.70±0.07	0.26±0.08

Vegetation structure and physicochemical characteristics

The structure of the mangrove vegetation varies between zones as well. The density of trees varies substantially between zones (ANOVA: $F_{5,5}$ = 2.486, ρ = 0.060). The *Ceriops* zone has the most mangrove species, whereas the *Avicennia* zone contains the fewest (Table 6). Meanwhile, the *Bruguiera* zone has the highest tree density (2720±563 stands/ha), while the *Lumnitzera* zone has the lowest (900±596 stands/ha). Almost as much as tree density, sapling category density varied substantially between zones (ANOVA; $F_{5,5}$ = 3.786, ρ = 0.011), with the *Ceriops* zone having the highest density (4540±3035 stands/ha). It demonstrates that the vegetation type that belongs to the sapling class dominated most of the mangrove species in the *Ceriops* zone, as opposed to the tree class. The number of seedlings discovered differed substantially across zones (ANOVA; $F_{5,5}$ = 4.170, ρ = 0.007), with the greatest number discovered in the *Rhizophora* zone (3200±2239 stands/ha). This is because most mangrove vegetation can produce progeny when it reaches the tree stage. In addition, it is corroborated by the viviparous reproduction of the mangrove genus *Rhizophora* (Aluri 2022; Wijaya et al. 2023).

Furthermore, the values for stem diameter, height, canopy cover, and mangrove health index are all significantly different: ANOVA; $F_{5,5}$ =7.563, ρ = 2.1 x 10^{-4}, ANOVA; $F_{5,5}$ = 14.818, ρ = 1.1 x 10^{-6}, ANOVA; $F_{5,5}$ = 2.645, ρ = 0.048, and ANOVA; $F_{5,5}$ = 3.454, ρ = 0.017 respectively. The larger stem diameter tended to be found in the *Sonneratia* zone (14.33±4.26 cm), while the smallest was in the *Ceriops* zone. This is due to the comparatively low density of mangroves in this zone, allowing optimal growth of mangrove vegetation without competition for nutrients and light (Sugiana et al. 2022). Regarding average mangrove height, the *Sonneratia* and *Rhizophora* zones have the highest values (Table 5). Because *Sonneratia* is located near the ocean and is frequently inundated by high tides, elevating the position of the stands to continue receiving sunlight is one of the adaptations necessary for its survival. It is also utilized with a dense *Rhizophora* zone when competition is required to acquire sunlight by elevating the stand's location (Mustika et al. 2014). In addition, the *Bruguiera* zone had the greatest canopy cover, whereas the *Lumnitzera* zone had the least (Table 6). The results are associated with the canopy growth distribution in each vegetation type, with *Bruguiera* mangroves growing conically upwards and *Lumnitzera* spreading (Dharmawan, 2020; Sugiana et al. 2022). Meanwhile, according to Dharmawan and Ulumuddin (2021), the overall health level of mangroves in all zones is moderate, with the lowest value found in the *Lumnitzera* zone (Table 6).

Physicochemical data revealed significant differences between mangrove zones, except for temperature (ANOVA; $F_{5,5}$ = 1.832, ρ = 0.145) and conductivity (ANOVA; $F_{5,5}$ = 2.714, ρ = 0.044). On average, porewater temperatures range from 26.2±0.9°C to 28.0±0.9°C, with *Ceriops* having the highest and lowest *Sonneratia* zones (Table 7). The dense canopy can block incoming sunlight, resulting in low shaft water temperature in the zone with the most canopy cover (Dewi et al. 2021; Sugiana et al. 2021), particularly for *Ceriops*. The pH of the porewater appears to differ significantly (ANOVA; $F_{5,5}$ = 6.390, ρ = 6.6 x 10^{-4}), with the highest average being 7.01±0.10 in the *Sonneratia* zone, as do salinity (31.51.0 ppt) and ORP (7.1±35.9 mV) (Table 7), with significance values of ANOVA; $F_{5,5}$ = 16.100, ρ = 5.5 x 10^{-7} and ANOVA; $F_{5,5}$ = 3.324, ρ = 0.020, respectively. The conductivity pattern was similar, although it varied significantly, with the highest value in the *Rhizophora* zone (47.0±1.46 mS cm^{-1}) and the lowest in the *Lumnitzera* zone (43.3±1.17 mS cm^{-1}) (Table 7). The variation in these figures is attributable to the proximity of the mangrove zone to the ocean. Salinity and conductivity levels will increase in these mangrove zones (near the sea) (Sugiana et al. 2021). The same holds for pH and ORP, as shaft water from more frequent tidal water rinses dissolves more atmospheric oxygen (Li et al. 2022).

The pH parameter was the only one that showed a significant difference (ANOVA; $F_{5,5}$ = 2.981, ρ = 0.031) in soil. The *Sonneratia* zone had the highest soil pH (6.63±0.39), while the *Bruguiera* zone had the lowest (5.94±0.50), almost identical to the pH of porewater (Table 7). With each significance value ANOVA; $F_{5,5}$ = 1.204, ρ = 0.374, ANOVA; $F_{5,5}$ = 1.204, ρ = 0.374, ANOVA; $F_{5,5}$ = 0.623, ρ = 0.686, and ANOVA; $F_{5,5}$ = 0.271, ρ = 0.919, total organic matter and its conversion parameters to total organic carbon, total nitrogen, and C/N ratio did not differ significantly between mangrove zones. The *Bruguiera* zone has the most significant proportion of organic matter and organic carbon, with values of 5.80±1.30% and 3.37±0.76%, respectively, while the *Lumnitzera* zone has the lowest, with values of 1.76±0.56% and 1.02±0.33% (Table 7). Similar findings for total nitrogen were obtained in the same area, with a value of 0.27±0.01%. However, the highest C/N ratio was found in the *Rhizophora* zone (16.72±15.70), while the lowest remained in the *Lumnitzera* zone (9.55±2.46) (Table 7). The vast amount of litter input from mangrove vegetation can generate high levels of available organic matter and nitrogen. The greater the number of mangroves in a zone, the greater the amount of residue produced, which increases organic matter and nitrogen content (Mulya and Arlen 2018; Torres et al. 2022). For example, *Rhizophora* and *Sonneratia* at the study site have reduced concentrations of organic matter due to frequent tidal rinses, resulting in an even distribution of organic matter from mangrove litter. The high organic matter content can also explain the low pH in the *Bruguiera* zone because decomposition requires a great deal of oxygen, lowering the sediment's pH level (Kim et al. 2021; Mamidala et al. 2022).

Table 6. Mangrove stand structure in Lembongan Island, Bali, Indonesia (superscript letters depict significant differences among zones ρ < 0.05)

Parameter	Zone					
	Avicennia	*Bruguiera*	*Ceriops*	*Lumnitzera*	*Rhizophora*	*Sonneratia*
Number of mangrove species	2	5	6	3	3	3
Tree density (stands/ha)	1180±853^{ab}	2720±563^{a}	1780±1564^{ab}	900±596^{b}	2040±1053^{ab}	1480±402^{ab}
Sapling density (stands/ha)	2220±672^{ab}	1740±1222^{ab}	4540±3035^{a}	2120±502^{ab}	2880±1773^{ab}	420±295^{b}
Number of seedlings (stands/ha)	2420±1156^{ab}	540±451^{a}	1100±1790^{ab}	560±913^{a}	3200±2239^{b}	140±114^{a}
Diameter (cm)	5.77±0.71^{a}	10.21±5.21^{ab}	4.85±1.50^{a}	5.28±1.02^{a}	6.65±2.36^{a}	14.33±4.26^{b}
Height (m)	4.82±1.30^{a}	9.45±2.38^{c}	5.22±1.57^{ab}	4.43±0.66^{a}	8.04±1.41^{bc}	10.64±1.35^{c}
Canopy (%)	55.11±18.26^{ab}	81.93±3.59^{a}	65.23±26.86^{ab}	42.98±9.53^{b}	64.43±16.74^{ab}	65.47±21.25^{ab}
Health index (%)	43.39±14.32^{ab}	65.99±5.45^{a}	56.33±14.87^{ab}	36.05±3.99^{b}	51.71±14.36^{ab}	56.14±17.13^{ab}

Table 7. Mangrove stand structure in Lembongan Island, Bali, Indonesia (superscript letters depict significant differences among zones ρ<0.05)

Object	Parameter	Zone					
		Avicennia	*Bruguiera*	*Ceriops*	*Lumnitzera*	*Rhizophora*	*Sonneratia*
Porewater	Temperature (°C)	27.1±0.7^{a}	27.3±1.4^{a}	26.2±0.9^{a}	27.6±0.9^{a}	26.6±1.5^{a}	28.0±0.9^{a}
	pH	6.29±0.20^{ab}	6.22±0.57^{a}	6.61±0.21^{abc}	6.32±0.04^{ab}	6.76±0.19^{bc}	7.01±0.10^{c}
	Salinity (ppt)	23.1±2.9^{ab}	27.0±3.6^{bc}	24.8±2.2^{ab}	20.8±1.0^{a}	29.4±1.3^{cd}	31.5±1.0^{d}
	ORP (mV)	-85.6±60.0^{a}	-59.6±32.4^{ab}	-40.6±37.9^{ab}	-63.4±44.9^{ab}	-21.6±22.4^{ab}	7.1±35.9^{b}
	Conductivity (mS cm^{-1})	44.2±2.55^{a}	46.6±3.32^{a}	44.6±1.74^{a}	43.3±1.17^{a}	47.0±1.46^{a}	46.3±1.26^{a}
Soil	pH	6.22±0.21^{ab}	5.94±0.50^{a}	6.24±0.26^{ab}	6.11±0.12^{ab}	6.45±0.27^{ab}	6.63±0.39^{b}
	TOM (%)	3.72±2.09^{a}	5.80±1.30^{a}	3.62±2.22^{a}	1.76±0.56^{a}	3.02±1.68^{a}	2.97±1.44^{a}
	TOC (%)	2.16±1.21^{a}	3.37±0.76^{a}	2.10±1.29^{a}	1.02±0.33^{a}	1.75±0.97^{a}	1.72±0.83^{a}
	TN (%)	0.27±0.30^{a}	0.27±0.01^{a}	0.17±0.12^{a}	0.12±0.06^{a}	0.15±11^{a}	0.12±0.06^{a}
	C/N Ratio	11.26±6.58^{a}	12.46±2.80^{a}	13.01±2.73^{a}	9.55±2.46^{a}	16.72±15.70^{a}	14.85±2.83^{a}

Table 8. Relationship between the gastropod's abundances in each media with the ecological conditions of the mangroves based on Pearson's correlation (symbol * indicated correlation significance at level ρ<0.05, while ** shows correlation significance at level ρ<0.01)

Subject	Parameter	Gastropod abundance		
		Soil	Trunk	Leaf
Porewater	Temperature (°C)	0.21	0.24	0.04
	Porewater pH	0.49**	0.48**	0.40*
	Salinity (ppt)	0.55**	0.67**	0.66**
	ORP (mV)	0.41*	0.47**	0.40*
	Conductivity (mS cm^{-1})	0.23	0.42*	0.35
Soil	Soil pH	0.34	0.34	0.30
	TOM (%)	-0.54**	-0.14	0.00
	TOC (%)	-0.54**	-0.14	0.00
	TN (%)	-0.58**	-0.36	-0.12
	C/N Ratio	0.03	0.22	0.02
Mangrove Stand Structure	Tree density (stands/ha)	0.04	0.12	0.21
	Sapling density (stands/ha)	-0.34	-0.42*	-0.24
	Seedling density (stands/ha)	0.00	-0.11	-0.04
	Diameter (cm)	0.45*	0.62**	0.47**
	Height (m)	0.41*	0.63**	0.60**
	Canopy (%)	0.02	0.13	0.23
	Health index (%)	0.05	0.20	0.34
	Distance to the sea (km)	-0.63**	-0.72**	-0.71**

Association of mangrove gastropods with vegetation structure and physicochemical characteristics

Several variables correlate substantially with the number of gastropods in each medium studied. While conductivity only correlates strongly with the abundance of gastropods in stems, pH, salinity, and ORP in pore water are closely correlated with the abundance of gastropods in all media (Table 8). The number of gastropods on the soil is inversely proportional to the amount of TOM, TOC, and TN (Table 8). While sapling density was significantly correlated only with the abundance of gastropods in the stems (trunk), stem diameter and stand height were significantly correlated with the number of gastropods in all media (Table 8).

Moreover, mangrove habitats are abundant near the coast, where salinity levels naturally fluctuate due to tide cycles and freshwater inflows. By modifying their osmotic and ionic equilibrium, salinity affects gastropods' physiology, behavior, and distribution. According to Kabir et al. (2014), mangrove gastropods typically survive in a wide spectrum of salinity conditions (euryhaline). Nevertheless, their tolerance differs by life stage and species. High salinity levels can reduce freshwater availability, causing dehydration and stress in gastropods. Meanwhile, low salinity can induce osmotic stress, impairing metabolism and reproduction (Chaparro et al. 2009). Therefore, the optimal salinity range for mangrove gastropods depends on species, life stage, and the magnitude and frequency of salinity fluctuations (Kabir et al. 2014; Hilmi et al. 2022), where the suitable salinity range for mangrove gastropod life in this research ranges from 20.8-31.5 ppt, with the maximum gastropod species found on the optimum salinity condition (*Sonneratia* zone).

The pH of the soil and water is a crucial factor in determining the abundance of mangrove gastropods. The acidity or alkalinity of a fluid is determined by its pH, which significantly affects the physiology, behavior, and distribution of gastropods (Imamsyah et al. 2020). The pH of the soil and water in mangrove habitats can vary based on tidal cycles, precipitation, and land use. The pH tolerance of mangrove gastropods varies according to species and life stage. Some gastropods prefer corrosive environments, whereas others favor alkaline environments. The pH of the soil can affect the availability and assimilation of nutrients by mangrove plants, thereby indirectly affecting the number of gastropods (Nuryanto et al. 2021). Low soil pH may reduce the availability of minerals such as calcium and magnesium, which are essential for the growth and development of mangrove plants (Sarker et al. 2021). This can reduce the number of abundances of gastropods by limiting their access to sustenance and habitat. In addition, the pH of the soil and water can interact with other environmental factors to affect their abundance and dispersion. The combination of corrosive water and high salt concentrations can increase the toxicity of metals and other pollutants, decreasing gastropod survival and reproductive success (Mearns et al. 2015). However, the pH in both soil and porewater still seems to be close to normal conditions (porewater: 6.22-7.01; soil: 5.94-6.63), so these impacts are still not visible in this study. For additional information, we also revealed that more abundant gastropods are found in pH-near normal conditions (pH = 7), such as the *Sonneratia* zone.

Oxidation and Reduction Potential (ORP) are important in gastropod abundance. The ORP tolerance of mangrove gastropods varies by species and life stage. High ORP levels affect the availability and absorption of nutrients by mangrove vegetation, indirectly affecting the number of gastropods (Pan et al. 2021). This condition could increase the availability of certain nutrients, such as nitrogen and phosphorus, essential for the growth and survival of mangrove vegetation (Echebiri et al. 2023). This can enhance food availability and habitat availability for gastropods, increasing abundance and diversity. The physiology and behavior of gastropods can be affected by reduced ORP levels. It may reduce the amount of oxygen in the water, limiting the respiration and metabolism of gastropods (Kabir et al. 2014). Consequently, their growth, reproduction, and survival may be compromised. That is why gastropods have more abundance in the zone with a positive ORP value (*Sonneratia* zone, ORP = 7.1 mV), than in the zone with a negative ORP value in this study.

Total Nitrogen (TN) in the soil is another important factor in determining the number of mangrove gastropods. Nitrogen is an essential nutrient for plants and animals and is involved in several metabolic processes, including protein synthesis, growth, and reproduction (Reis et al. 2017). There is a wide variety of foraging strategies and preferences among mangrove gastropods, and the quantity and quality of food supplies can influence their abundance and diversity. Soil TN controls the growth and productivity of mangrove plants, which may modify the amount and quality of food available to gastropods. High levels of soil TN can stimulate plant growth and the development of leaves, fruits, and flowers, providing gastropods with sustenance and shelter (Alongi 2018). However, comparable to the availability of organic matter, the total nitrogen content of the soil also contributes to low pH, threatening the existence of mangrove gastropods (Hasibuan et al. 2021). That is why the *Sonneratia* zone with the lowest TN value of 0.12% has more abundant gastropods than other zones, except for *Lumnitzera* zones where the abundance of gastropods tends to be influenced by other factors such as the mangrove stand structures.

Mangrove density is also a crucial factor influencing the abundance of mangrove gastropods. A dense mangrove population can create an ideal gastropod habitat by providing ample sustenance and cover, as measured by mangrove diameter and height. In addition, it may protect gastropods from predators, reduce water velocity and energy, and increase sediment deposition (Hilmi et al. 2022). These elements can contribute to developing an ecosystem where gastropods can subsist, mature, reproduce, and flourish, increasing their abundance and diversity (Basyuni et al. 2022). In addition, the density of mangroves can influence the abundance and distribution of gastropods when combined with other environmental stressors. For instance, a combination of low mangrove density and high sedimentation rates may result in the burial of gastropod habitat and a decrease in their survival rate (Ellis et al. 2004).

In Summary, various environmental factors influence the population of mangrove gastropods. A primary factor is the distance from the sea; the abundance of gastropods is inversely related to the distance of the mangrove plot from the sea. The quantity of organic matter and nitrogen in the soil dictates the growth and reproduction of mangrove plants, which provide gastropods with food and habitat. The salinity and pH of the water can affect the physiology and behavior of gastropods. Other factors are the density of mangroves, including their diameter and height, affecting habitat availability and predator protection, and Oxidation and Reduction Potential (ORP), which impact the nitrogen supply for mangrove plants, thereby altering the gastropod population. When these characteristics are combined with other stresses, such as pollution from human activities, the distribution and abundance of mangrove gastropods may change.

The mangrove - gastropod ecosystem is complex. Increasing our understanding of the many factors impacting the ecosystem is vital to protecting this important ecosystem at the marine-terrestrial boundary.

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